CHAPTER 9

Modeling Tools

A. Introduction

A variety of models are available that are related to assessment of nutrients in lakes and reservoirs. The use of models can include a wide range of applications, from evaluating in-lake trophic conditions to estimating loading from an entire watershed. After providing a brief review of lake and reservoir modeling frameworks, this chapter focuses on two areas where modeling can be applied with regard to the development and management of nutrient criteria. The first area is prediction or extrapolation of reference conditions, which are used as a basis for setting nutrient criteria (see Chapter 6). The second area deals with the use of models as tools for management in the watershed once nutrient criteria have been established and implemented (see Chapter 8). Readers are encouraged to consult the following references for more in-depth information on lake and reservoir modeling:

- Chapra, S. 1997. *Surface Water-Quality Modeling*. McGraw-Hill Publishers, Inc.
- Thomann, R.V., and J.A. Mueller. 1987. *Principles of Surface Water Quality Modeling and Control*. Harper & Row, New York.
- U.S. Environmental Protection Agency. 1990. *The Lake and Reservoir Restoration and Guidance Manual*. EPA/440/4-90/006. Office of Water, Washington, DC.
- U.S. Environmental Protection Agency. 1997. *Compendium of Tools for Watershed Assessment and TMDL Development*. EPA /841/b-97/006. Office of Water, Washington, DC.

B. Review of Lake/Reservoir Eutrophication Modeling Frameworks

Modeling frameworks to simulate the impact of nutrients on the quality of standing waters can be divided into three general categories:

- Empirical models
- Nutrient budget/mass balance models
- Nutrient food chain models

These models are listed in order of increasing complexity and higher mechanistic definition. It should be stressed that higher complexity does not necessarily connote inherent superiority.

1. Empirical Models

Empirical models are graphical approaches based on measurements from many lakes and reservoirs. The pioneering work in this area was performed by Vollenweider (1968, 1976) and Dillon and Rigler

(1974). Other investigators, notably Rast and Lee (1987) and Reckhow (1977), extended and broadened the approach.

Empirical models can be loosely divided into two categories: (1) phosphorus loading plots and (2) trophic parameter correlations. As depicted in Figure 9.1, phosphorus loading plots typically graph lakes on a two-dimensional space with the log of the areal phosphorus loading on the ordinate and the log of hydrogeometric parameters on the abscissa. For example, Figure 9.1 has the log of ratio of the lake's mean depth to its residence time as the abscissa. Lines are then superimposed to demarcate different trophic states. The plots then can be used to predict the trophic state of a lake based on its loading and hydrogeometry.

It should be noted that a number of investigators (e.g., Thomann, 1977; Chapra and Tarapchak, 1976; Vollenweider, 1976) have illustrated how such plots can be related to and derived from the simple phosphorus budget models to be described in the next section. Thus, aside from predicting trophic state, the plots can be structured to predict in-lake TP concentration as a function of loads.

Trophic parameter correlations are usually log-log plots relating two trophic parameters. For example, Figure 9.2 shows a correlation between chlorophyll *a* and TP concentration.

Empirical models have several strengths and weaknesses. Their strengths are:

- They are extremely easy to use.
- They provide a quick means to identify "outlier" lakes.
- If they are based on regional or local databases of relatively homogeneous populations of lakes (e.g., lime lakes in northern Michigan), they are capable of producing adequate predictions.

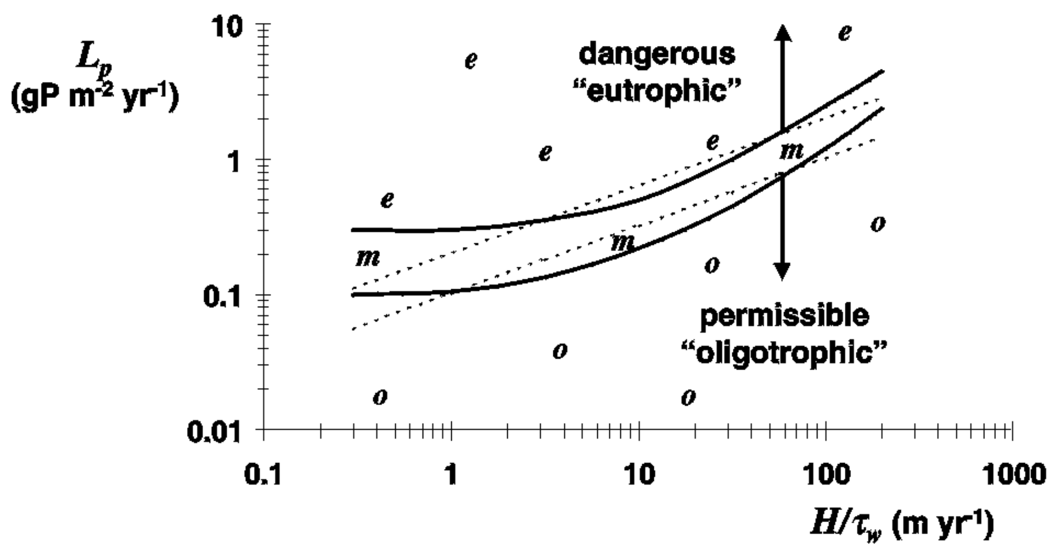

Figure 9.1. Vollenweider's loading plot (1975).

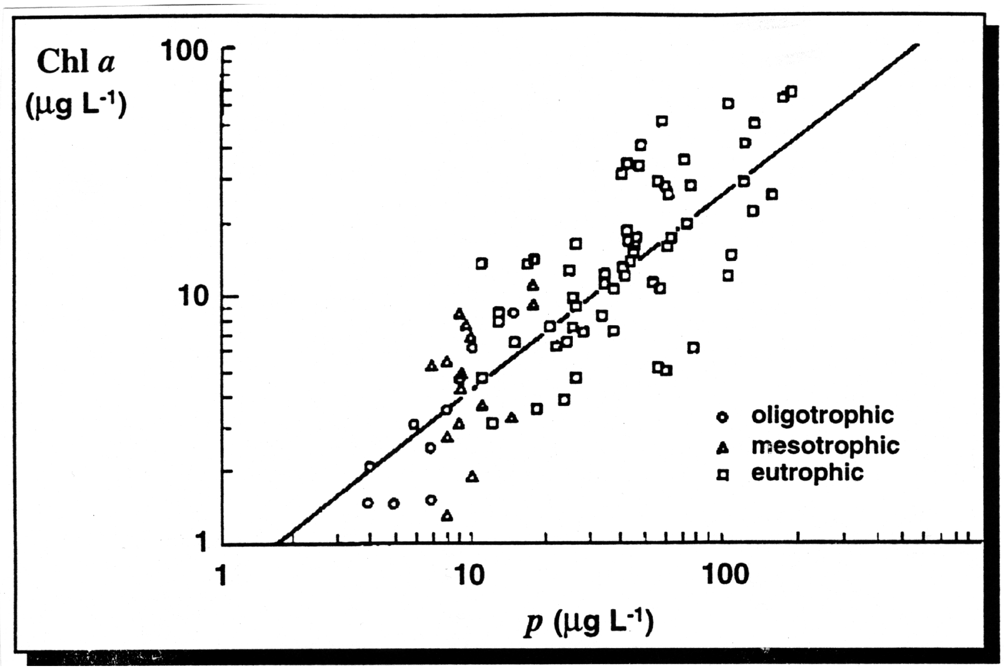

Figure 9.2. Relationship between chlorophyll and phosphorus. Trophic parameter correlations are usually log-log plots relating two trophic parameters. For example, Figure 9.2 shows a correlation between chlorophyll *a* and TP concentration.

Their primary weakness relates to the fact that, if based on global data (e.g., north temperate lakes), they tend to have very large standard errors of prediction. Unfortunately, the plots often are presented in a manner that does not make this uncertainty explicit. Hence, naive users can develop predictions and are unaware that their results may have substantial errors. A number of investigators, notably Reckhow and Walker, have worked to include uncertainty estimates with empirical model predictions.

In summary, although they have some utility, empirical models (and particularly those based on global data) do not usually have the required precision upon which high-cost decisions can be made. As such, empirical models should be relegated to broad screening applications and for identifying atypical lakes. However, they may have sufficient precision if developed and applied for regional populations of lakes and reservoirs.

2. Nutrient Budget/Mass Balance Models

Early on (e.g., Vollenweider, 1969), it was recognized that simple mass balance models could provide similar predictions to phosphorus loading plots. These models do not attempt a detailed characterization of the division of phosphorus within the water column. Rather, they focus of characterizing major inputs and outputs to predict the long-term trends of a lake's response to loading changes.

The simplest example of a TP budget model was developed by Vollenweider (1969) and modified by Chapra (1975):

$$V\,\frac{dp}{dt} = W - Qp - vAp$$

where V = volume, p = TP concentration, t = time, W = loading, Q = outflow, v = an apparent settling velocity, and A = surface area. As depicted in Figure 9.3a, the key feature of this model is the simple way in which it characterizes the input-output terms for TP. In particular, it attempts to characterize sedimentation losses as a simple one-way settling of TP.

As with loading plots, steady-state solutions can be developed by setting the derivative to 0 and solving for $p = W/(Q + vA)$. If levels of TP can be associated with trophic state, the model can be used to determine the loading required to maintain a particular lake at a desired quality in a fashion similar to the loading plots. The model also provides a framework to determine the temporal response of a lake to loading changes. Thus, it has the advantage over loading plots in that system dynamics can be characterized.

Phosphorus budget models have been improved in several ways:

- For incompletely mixed systems, the lake can be divided into a system of interconnected well-mixed systems. This can be done horizontally or vertically. For example, Chapra (1979)used two mass balances to characterize a lake with a major embayment. In a similar manner, O'Melia (1972) and others have vertically divided the water column of thermally stratified lakes into surface and bottom layers

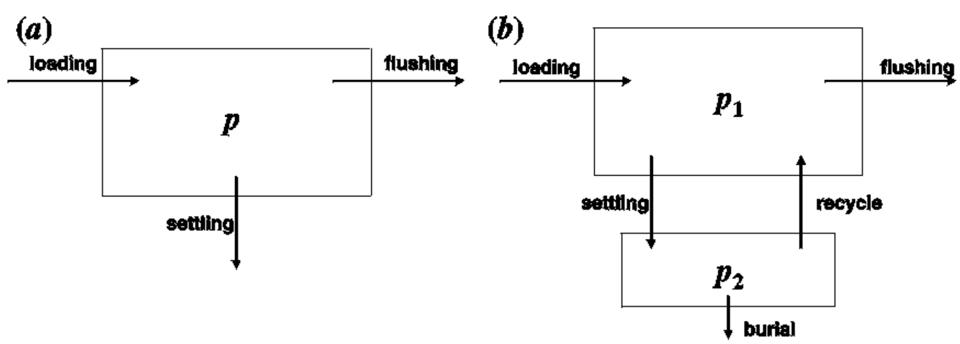

Figure 9.3. Two phosphorus budget models: (a) characterizes sedimentation as a simple one-way loss to the sediments and (b) includes sediment feedback

- Efforts have been made to better characterize sediment–water interactions. Chapra and Canale represented a lake and its underlying sediments as a two-layer system (Figure 9-3b). Along with phosphorus settling, this model also allows sediment feedback. A simple oxygen model is used to simulate hypolimnetic anoxia, which triggers sediment release of TP into the overlying waters. This mechanism is significant, because sediment feedback can retard the recovery of lakes after TP load reductions.

- Hybrid models have been developed that use mass balance and multiple segments to characterize transport, but to quantify kinetics, they use empirically derived relationships. Walker's BATHTUB model for reservoirs is a good representative of this type.

In summary, the phosphorus budget models use simple mass balance to characterize how phosphorus levels change in lakes in response to load modifications. Thus, the assumption is made that "as goes phosphorus, so goes eutrophication." Such models can be useful for simulating the long-term trends in the quality of phosphorus-limited lakes and reservoirs.

3. Nutrient/Food Chain Models

In contrast to the budget models described above, nutrient/food chain models attempt to mechanistically characterize the partitioning of matter within the lake on a seasonal timeframe. These models were first developed in the 1970's to expressly address the impact of nutrients on natural waters (e.g., Chen, 1970; Chen and Orlob, 1975; Di Toro et al., 1971; Canale et al., 1974). They typically have a number of common characteristics, including transport characterization and kinetic characterization.

■ Transport Characterization

An effort is made to characterize the internal physics of a lake or reservoir. Thus, rather than representing the lake as a single well-mixed entity, multiple segments typically are used to model the internal physics. The most common approach is to use two vertical layers to characterize thermal stratification. More refined vertical segmentation is sometimes used to resolve hypolimnetic gradients, particularly near the sediment–water interface. In addition, multiple horizontal segments are employed for incompletely mixed systems such as elongated reservoirs. There are two ways in which the magnitude of mixing and interflow between segments is modeled:

- First, it can be treated as a model input. This is done by specifying turbulent diffusion coefficients and intersegment flows. In many such applications, the temperature distribution is also treated as a model input.

- Second, water motion can be calculated internally using energy and momentum balances. Thus, a separate hydrodynamic model is used to supply the physics. In some cases, temperature is calculated as a part of the hydrodynamic simulation.

■ Kinetic Characterization

Matter in the lake is divided into several forms of nutrients and a food chain. A typical example of how this is done is shown in Figure 9.4. Several nutrients are typically included. Hence, the model is capable of simulating multiple nutrient limitation. As shown in the figure, phosphorus and nitrogen are the common choices. These usually are divided into available and unavailable components. The latter can be broken down further, for example, into dissolved and particulate fractions.

The food chain shown in the figure consists of a single algal compartment, along with two zooplankton compartments. Algae growth is calculated as a function of temperature, light, and available nutrient concentrations. All other rates are temperature dependent. All three organisms experience respiration/excretion losses. As shown in the figure, these can be released to either the available or unavailable nutrient pools. Grazing is inefficient, with a fraction of the grazing egested to the unavailable pools.

This framework can be simplified by dropping a nutrient (usually nitrogen). It is more likely to be made more complicated by adding nutrients (e.g., silicon) or making them more refined (e.g., breaking the unavailable components into dissolved and particulate fractions). The food chain can be made more complex by breaking the single algal compartments into components (e.g., diatoms, greens and blue-greens). Similar refinements can be made to the zooplankton. When this is done, feeding preferences usually must be specified. It should be noted that other variables such as oxygen and pH can be integrated into these frameworks. In these cases, it is usually necessary to simulate organic carbon.

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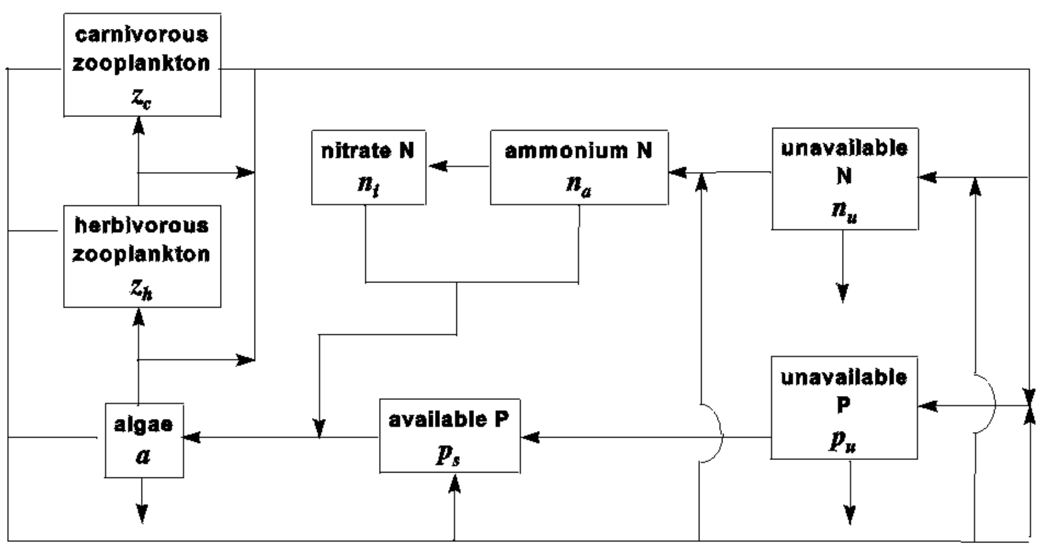

Figure 9.4. Kinetic segmentation.

C. Model Use for Aiding in the Establishment of Reference Conditions

1. Morphoedaphic Index

The morphoedaphic index (MEI) is the ratio of total dissolved solids in lake water to the mean depth of the lake. Early studies suggested that the MEI was correlated with fish and phytoplankton production of lakes (e.g., Rawson, 1952; Ryder, 1965; Oglesby, 1977). The MEI approach was extended by Vighi and Chiaudani (1985) to predict phosphorus concentrations resulting from natural background loading in undisturbed watersheds. This prediction can, therefore, be used to predict reference phosphorus concentrations.

Using data from 53 cool-temperate lakes of North America and Europe, with negligible anthropogenic phosphorus input, Vighi and Chiaudani (1985) developed a regression equation predicting mean phosphorus concentration from the MEI, where MEI was calculated using either alkalinity or conductivity as a surrogate for total dissolved solids:

$$\text{Log } [P] = 1.48 + 0.33 \text{ Log MEI}_{alk};\ r = 0.83$$
$$\text{Log } [P] = 0.75 + 0.27 \text{ Log MEI}_{cond};\ r = 0.71.$$

Analysis of covariance showed no significant differences between the European and North American lakes, and lakes with known anthropogenic phosphorus inputs all fell above the estimated regression line for undisturbed lakes (Vighi and Chiaudani 1985). This MEI model is used by the Minnesota Pollution Control Agency (MPCA) to estimate background phosphorus concentrations and develop reference conditions for oligotrophic and mesotrophic lakes (see text box at end of this chapter). Many Minnesota lakes are similar to the lakes for which the model was developed: relatively deep cool-temperate lakes of glacial origin, which are oligotrophic to mesotrophic. The approach has not been calibrated or confirmed for shallow lakes, naturally eutrophic lakes, warm-temperate lakes, or impoundments. The MEI approach is simple and appears to be highly successful for a limited set of cool-temperate lakes. However, because its use has not been widespread (possibly because of its simplicity), it has not been calibrated and tested for a wider variety of lakes. Because this approach has potential, it needs to be recalibrated and tested with regional reference lake data sets.

2. Mass Balance Models with Loading Estimation

■ Mass Balance Models

Mass balance models are a means of estimating concentrations of nutrients using knowledge of loading into a lake and hydrology of a lake. A mass balance model by itself will not establish reference conditions—it will predict nutrient concentrations given certain loading values. Therefore, to use a mass balance model to derive reference conditions for a lake, an estimate of the natural background nutrient loading to the lake is required. In the most basic steady-state mass balance phosphorus model, the equation for prediction of the concentration of phosphorus in a reservoir is produced by rearranging the mass balance equation (see Chapter 2) and solving for the concentration in the lake:

Concentration (lake) = Concentration (incoming water) × Fraction NOT Sedimented
or
$$C_L = C_i \times (1 - R)$$

C_L and C_i are concentrations of the material in the lake (L) and in the incoming water (i), and R is the amount retained in the water column. C_i is usually calculated as the nutrient loading, J (mg/year), divided by the amount of water flowing out of the reservoir (m^3/year) to compensate for evaporation from the reservoir surface. The letter R represents the fraction of the material retained in the lake (i.e., sedimented). By subtracting the fraction sedimented from 1, the term "(1−R)" represents the fraction of the incoming concentration that can be found in the reservoir water (Dillon and Rigler, 1974). There are a number of methods for estimating (1−R), but one of the simplest, and yet one of the most consistently accurate, has been found to be:

$$1 - R = \frac{1}{1 + sT}$$

where T is the water residence time (Vollenweider, 1976; Larsen and Mercier, 1976). This equation implies that the retention of materials in the reservoir increases the longer the water remains in the reservoir (as the water residence time increases). This makes intuitive sense because it means there is more time for the phosphorus to sediment out of the water column. The effect is that the longer the water residence time, the lower the expected phosphorus concentrations in the reservoir. This becomes especially significant because watershed development not only affects nutrient loading through increases in nutrient concentration but also increases water flow into the reservoir, thus decreasing the water residence time and further increasing the in-reservoir phosphorus concentration.

The final predictive equation becomes:

$$C_L = C_i \frac{1}{1 + s\sqrt{T}}$$

In the context of estimating reference conditions, models of this type can be used to estimate the potential predisturbance condition of the water body. The incoming concentration (C_i) does not necessarily have to represent the present or future concentration in the incoming stream. If there are undisturbed streams in the region, then the concentrations in those streams can be used instead to estimate the theoretical undisturbed condition. Some error would be introduced because water flow, and therefore the water residence time (T), also may be affected by disturbance; the estimated value would then underestimate the reference phosphorus condition.

■ Receiving Water Models

Receiving water models are used to examine the interactions between loadings and response, evaluate loading capacities, and test various loading scenarios. As with watershed loading models, receiving water models vary widely in complexity. For traditional point source abatement, where biodegradable pollutant discharges are the major concern, simple steady-state models of the dissolved oxygen balance are commonly used by planners and pollution control authorities. For assessment of eutrophication and toxics, more comprehensive models have evolved to incorporate a wider range of processes. Other recent reviews of receiving water models include Ambrose et al. (1995).

A fundamental concept for the analysis of receiving water body response to point and nonpoint source inputs is the principle of mass balance (or continuity). Receiving water models typically develop a mass balance for one or more interacting constituents, taking into account three factors: transport through the system, reactions within the system, and inputs into the system. The first factor describes the hydrologic and hydrodynamic regime of the water system; the second, the biological, chemical, and physical reactions that affect constituents; and the third, the inputs to or withdrawals from the system because of anthropogenic activities and natural phenomena (O'Conner et al., 1975). The complexity of a receiving water model depends on the way in which these three factors are incorporated. The simplest models use a steady-state one-dimensional framework with steady inputs. The more complex models typically use hydrodynamic relationships, consider interactions between constituents, allow distributed nonpoint inputs, and are capable of providing dynamic, multidimensional simulations.

The various physical, chemical, and biological processes considered by a receiving water model are represented mathematically by mechanistic and/or empirical relationships between forcing functions and state variables (Jorgensen, 1995). Forcing functions are variables or functions of an external nature that are regarded in the model formulation as directly influencing the state of the receiving water body. Point and nonpoint source loadings to the water body are examples of forcing functions; other examples are temperature and solar radiation. State variables, such as dissolved oxygen and chlorophyll *a* concentrations, define the state of the receiving water body. When the predicted values of state variables change because of changes to forcing functions, the state variables are regarded as model outputs. In the context of TMDL development, the typical situation would involve manipulating forcing functions that are controllable (e.g., point source loadings and, to an extent, nonpoint source loadings) and observing the effect on state variables of interest.

Receiving water models are typically described in terms of their representation of space (spatial domain), time (temporal domain), flow simulation (hydrodynamics), transport processes, inputs (forcing functions), and state variables. Other factors considered in the review of receiving water models include user interface and inherent application complexity. Receiving water models can be grouped generally into three classes—hydrodynamic models, steady-state water quality models, and dynamic water quality models. Water quality models can simulate the chemical and biological processes that occur within a water body system based on external and internal inputs and reactions. Because steady-state water quality models are the most commonly used and the easiest to implement, a select few are described below. For more information on hydrodynamic models and dynamic water quality models, the reader is referred to U.S. EPA, 1997.

Watershed and Lake Modeling Software (EUTROMOD)

EUTROMOD is a spreadsheet-based modeling procedure for eutrophication management developed at Duke University and distributed by the North American Lake Management Society (Reckhow, 1990). The steady-state modeling system allows for internal calculations of both nonpoint source loading and lake response. The system estimates nutrient loadings, various trophic state parameters, and trihalomethane concentrations in lake water. The computation algorithms used in EUTROMOD were developed based on statistical relationships and a continuously stirred tank reactor model. Model results include the most likely predicted phosphorus and nitrogen loading for the watershed and for each land use category. The model also determines the lake response to various pollution loading rates. The spreadsheet capabilities of the model allow graphical representations of the results and data export to other spreadsheet systems for statistical analyses. The model was used in conjunction with a Geographic Information System (GIS) for establishing TMDLs to Wister Lake, Oklahoma (Hession et al., 1995).

Seasonal and Long-Term Trends of Total Phosphorus and Oxygen in Stratified Lakes (PHOSMOD)

PHOSMOD is a budget model that can predict the long-term response of a lake to changes in phosphorus loading (Chapra and Canale, 1991). In the model, the lake is treated as two layers: a water layer and a surface sediment layer. A TP budget for the water layer is developed with inputs from external loading and recycling from the sediments and considering losses due to flushing and settling. In the sediment layer budget, TP is gained by settling and lost by recycling and burial. The sediment-to-water recycling is dependent on the levels of sediment TP and hypolimnetic oxygen, with the concentration of the latter estimated with a semiempirical model. Chapra and Canale (1991) present an application of the model and an analysis to demonstrate how the model predictions replicate in-lake changes not possible with simpler phosphorus budget models.

BATHTUB

FLUX, PROFILE, and BATHTUB (Walker, 1986) are a collection of programs designed to assist in the data reduction and model implementation phases of eutrophication studies in lakes and reservoirs. FLUX is a tool for data reduction and preprocessing of tributary nutrient loadings from grab sampling and flow records. The program can assist in error detection and sampling program design. PROFILE provides displays of lake water quality data and assists in analysis of sampling information. Data analysis procedures include hypolimnetic oxygen depletion rates, spatial and temporal variability, and statistical summaries. BATHTUB allows the user to segment the lake into a hydraulic network. Nutrient balance and eutrophication models can be applied to the network to assess advection, dispersion, and nutrient sedimentation. Empirical relationships that have been calibrated and tested for reservoir applications are used to predict eutrophication-related water quality conditions. The segmented structure of BATHTUB allows its application to single reservoirs, partial reservoirs, networks of reservoirs, or collections of reservoirs, permitting regional comparative assessments of reservoir conditions, controlling factors, and model performance. Inputs and outputs can be expressed in probabilistic terms to account for limitations in input data and intrinsic model errors. The programs and models have been applied to U.S. Army Corps of Engineer reservoirs (Kennedy, 1995), as well as a number of other lakes and reservoirs. BATHTUB has been cited as an effective tool for lake and reservoir water quality assessment and management, particularly where data are limited (Ernst et al., 1994).

AQUATOX

A receiving water and food chain model will soon be released by the EPA Office of Science and Technology. AQUATOX is designed to simulate the biological, physical, and chemical processes within a water body in response to stressors. Parameters include phosphorus, nitrogen, chlorophyll *a*, Secchi depth, dissolved oxygen, macrophytes, and several trophic groups of invertebrates and fish. It is a time-variable model expected to predict seasonal changes, such as when different algal groups may bloom and lake ecosystem responses to changes in nutrient loading or other management measures.

AQUATOX is expected to provide the user with a great deal of data in the form of data libraries, which can be used “as is” or edited by the user to better characterize a water body. It has been validated for nutrients on a stratified eutrophic lake in New York and a reservoir in Iowa. It will be undergoing peer review in 2000.

■ Simple Watershed-Scale Loading Models

Watershed-scale loading models are good choices to use to estimate nutrient loads entering lakes and reservoirs. For discussion purposes, watershed-scale loading estimation methods can be divided into three general categories based on complexity, operation, time step, and simulation technique—simple methods, mid-range models, and detailed models (U.S. EPA, 1997). Simple methods are the most suitable for aiding in the prediction of reference conditions. Mid-range and detailed watershed-scale loading models are more advantageous for watershed management applications, as detailed below.

Simple methods are generally empirical in nature. The major advantage of empirical methods is that they can provide a means of developing regional reference conditions with less effort and data requirements than more complex simulation models. These methods are compilations of expert judgment and empirical relationships between physiographical characteristics of the watershed and pollutant export, or they are estimates based on existing data. They are the most suitable models for developing regional reference conditions and making regional predictions, but they are the least suitable models for aiding watershed management and lake management decisions.

Typically, simple methods rely on large-scale aggregation and neglect important features of small patches of land. They rely on generalized sources of information and therefore have low to medium requirements for site-specific data. Default values provided for these methods are derived from empirical relationships that are evaluated based on regional or site-specific data. The estimations usually are expressed as mean annual values. Simple methods provide aggregated (e.g., annual average) estimates of sediment and pollutant loadings, but they have limited predictive capability for short-term loading or events. The empiricism contained in the models limits their transferability to other regions. Because they often neglect seasonal variability, simple methods might not be adequate to model short-term water quality problems for which specific loadings of shorter duration are important.

Pollutant loads are determined from export coefficients (e.g., the Watershed model) or as a function of the sediment yield (e.g., EPA screening procedures, SLOSS-PHOSPH). The Simple Method, the U.S. Geological Survey (USGS) regression method, and the Federal Highway Administration model are statistically based approaches developed from past monitoring information. In general, the application of empirical models is limited to the watershed types for which they were developed, with similar land uses or activities. Applications to new areas requires recalibration with relevant data.

Selected simple empirical watershed-scale loading models are described below (U.S. EPA, 1997).

Reckhow-Simpson Model

This approach (Reckhow and Simpson, 1980) uses a simple mass balance model with empirical predictions of phosphorus loading rates from different land uses to predict mean lake phosphorus concentration. The mass-balance equation uses phosphorus loading, water loading, and an empirically derived settling velocity for phosphorus to estimate phosphorous concentration. Users must derive high, median, and low estimates of phosphorus export coefficients from agricultural, forest, and urban land, as well as septic fields and precipitation. The high and low estimates are used to bracket uncertainty of the best estimate.

EPA Screening Procedures

The EPA screening procedures, developed by the EPA Environmental Research Laboratory in Athens, Georgia (McElroy et al., 1976; Mills, 1985), include methodologies to calculate pollutant loads from point and nonpoint sources, including atmospheric deposition, for preliminary assessment of water quality. The procedures consist of loading functions and simple empirical expressions relating nonpoint pollutant loads to other readily available parameters. Data required generally include information on land use/land cover, management practices, soils, and topography. Although these procedures are not coded into a computer program, several computer-based models have adapted the loading function concept to predict pollutant loadings. An advantage of this approach is the possibility of using readily available data as default values when site-specific information is lacking. Application of these procedures requires minimum personnel training and practically no calibration. However, application to large, complex watersheds should be limited to planning activities. Many of the techniques included in the manual were incorporated into current models such as Generalized Watershed Loading Functions (GWLF).

USGS SPARROW Regression Approach

The SPARROW regression is very similar to the storm runoff model (described below), and is based on hydrologic unit-level discharge data from USGS gaging stations (Smith et al., 1997). The model was developed from nationwide data (414 stations for up to 15 years). The SPARROW approach considered four sources of total nitrogen and TP: point sources, fertilizer, livestock waste, and runoff from nonagricultural land. Atmospheric nitrogen deposition also was included in the nitrogen model (Smith et al., 1997). The model estimated land surface delivery (of nonpoint source runoff) and instream decay (denitrification or settlement) of the nutrients. A possible drawback of the approach for estimating reference conditions is that nonagricultural land uses were lumped as a single category (Smith et al. 1997). The model was developed from nationwide data; use of this method for extrapolation of regional reference conditions would require reestimation and calibration using relevant regional data. While time consuming and data intensive, regional recalibration should result in more precise estimates than the national model.

Simple Method

The Simple Method is an empirical approach developed for estimating pollutant export from urban development sites in the Washington, DC, area (Schueler, 1987). It is used at the site-planning level to predict pollutant loadings under a variety of development scenarios. Its application is limited to small drainage areas of less than a square mile. Pollutant concentrations of phosphorus, nitrogen, chemical oxygen demand, biochemical oxygen demand, and metals are calculated from flow-weighted concentration values for new suburban areas, older urban areas, central business districts, hardwood forests, and urban highways. The method relies on the National Urban Runoff Program (NURP) data for default values (U.S. EPA, 1983). A graphical relationship is used to determine the event mean sediment concentration based on readily available information. This method is not coded into a computer program but can be easily implemented with a hand-held calculator.

USGS Regression Approach

The regression approach developed by USGS researchers is based on a statistical description of historic records of storm runoff responses on a watershed level (Tasker and Driver, 1988). This method may be used for rough preliminary calculations of annual pollutant loads when data and time are limited. Simple regression equations were developed using available monitoring data for pollutant discharges at 76 gaging stations in 20 States. Separate equations are given for 10 pollutants, including dissolved and total nutrients, chemical oxygen demand, and metals. Input data include drainage area, percent imperviousness, mean annual rainfall, general land use pattern, and mean minimum monthly temperature. Application of this method provides storm-mean pollutant loads and corresponding confidence intervals. The use of this method as a planning tool at a regional or watershed level might require preliminary calibration and verification with additional, more recent monitoring data.

Simplified Pollutant Yield Approach (SLOSS-PHOSPH)

This method uses two simplified loading algorithms to evaluate soil erosion, sedimentation, and phosphorus transport from distributed watershed areas. The SLOSS algorithm provides estimates of sediment yield, whereas the PHOSPH algorithm uses a loading function to evaluate the amount of sediment-bound phosphorus. Application to watershed and subwatershed levels was developed by Tim et al. (1991) based on an integrated approach coupling these algorithms with VirGIS (Virginia GIS). The approach was applied to the Nomini Creek watershed, Westmoreland County, Virginia, to target critical areas of nonpoint source pollution at the subwatershed level (U.S. EPA, 1992c). In this application, analysis was limited to phosphorus loading; however, other pollutants for which input data or default values are available can be modeled in a similar fashion. The approach requires full-scale GIS capability and trained personnel.

Watershed

Watershed is a spreadsheet model developed at the University of Wisconsin to calculate phosphorus loading from point sources, combined sewer overflows, septic tanks, rural croplands, and other urban and rural sources. It can be used to evaluate the tradeoffs between control of point and nonpoint sources (Walker et al., 1989). It uses an annual time step to calculate total pollution loads and to evaluate the cost-effectiveness of pollution control practices in terms of cost per unit load reduction. The program uses a series of worksheets to summarize watershed characteristics and to estimate pollutant loadings for uncontrolled and controlled conditions. Because of the simple formulation describing the various pollutant loading processes, the model can be applied using available default values with minimum calibration effort. Watershed was applied to study the tradeoffs between controlling point and nonpoint sources in the Delavan Lake watershed in Wisconsin.

Federal Highway Administration Model

FHWA's Office of Engineering and Highway Operations has developed a simple statistical spreadsheet procedure to estimate pollutant loading and impacts to streams and lakes that receive highway storm water runoff (FHWA, 1990). The procedure uses several worksheets to tabulate site characteristics and other input parameters, as well as to calculate runoff volumes, pollutant loads, and the magnitude and frequency of occurrence of instream pollutant concentrations. The FHWA model uses a set of default values for pollutant event-mean concentrations that depend on traffic volume and the rural or urban setting of the highway's pathway. FHWA uses this method to identify and quantify the constituents of highway runoff and their potential effects on receiving waters and to identify areas that might require controls.

Watershed Management Model

The Watershed Management Model (WMM) was developed for the Florida Department of Environmental Regulation for watershed management planning and estimation of watershed pollutant loads (Camp et al., 1992). Pollutants simulated include nitrogen, phosphorus, lead, and zinc from point and nonpoint sources. The model is implemented in the Lotus 1-2-3 spreadsheet environment and will thus calculate standard statistics and produce plots and bar charts of results. Although it was developed to predict annual loadings, WMM can be adapted to predict seasonal loads provided that seasonal event mean concentration data are available. In the absence of site-specific information, the event concentrations derived from NURP surveys may be used as default values. The model includes computational components for stream and lake water quality analysis using simple transport and transformation formulations based on travel time. WMM has been applied to several watersheds, including the development of a master plan for Jacksonville, Florida, and the Part II estimation of watershed loadings for the National Pollutant Discharge Elimination System permitting process. It also has been applied in Norfolk County, Virginia; to a watershed management plan for North Carolina; to a wasteload allocation study for Lake Tohopekaliga, near Orlando, Florida; and for water quality planning in Austin, Texas (Pantalion et al., 1995).

D. Watershed Management Models

As watershed-based assessment and integrated analysis of point and nonpoint source pollution have become the focus of governmental water programs, modeling has been used to evaluate a wider range of pollutant generation, transport, control, and environmental response issues (U.S. EPA, 1997). Management goals such as pollutant source identification and prioritization, prediction and estimation of lake and reservoir response to watershed nutrient control practices, and long-term evaluation of a watershed system's response to management efforts can be addressed using modeling techniques. This section discusses the use of watershed loading models and receiving water models for management purposes.

1. Mid-Range Watershed-Scale Loading Models

The advantage of mid-range watershed-scale loading models is that they evaluate pollution sources and impacts over broad geographic scales and therefore can assist in defining target areas for pollution mitigation programs on a watershed basis. Several mid-range models are designed to interface with GISs, which greatly facilitate parameter estimation. Greater reliance on site-specific data gives mid-range models a relatively broad range of regional applicability. However, the use of simplifying assumptions can limit the accuracy of their predictions to within about an order of magnitude (Dillaha, 1992) and can restrict their analysis to relative comparisons.

This class of model attempts a compromise between the empiricism of the simple methods and the complexity of detailed mechanistic models. Mid-range models use a management-level approach to assess pollutant sources and transport in watersheds by incorporating simplified relationships for the generation and transport of pollutants. Mid-range models, however, still retain responsiveness to management objectives and actions appropriate to watershed management planning (Clark et al., 1979). They are relatively simple and are intended to be used to identify problem areas within large drainage basins or to make preliminary, qualitative evaluations of best management practices (BMP) alternatives (Dillaha, 1992).

Unlike the simple methods, which are restricted to predictions of annual or storm loads, mid-range tools can be used to assess the seasonal or interannual variability of nonpoint source pollutant loadings and to assess long-term water quality trends. Also, they can be used to address land use patterns and landscape configurations in actual watersheds. They are based primarily on empirical relationships and default values. In addition, they typically require some site-specific data and calibration.

Mid-range models are designed to estimate the importance of pollutant contributions from multiple land uses and many individual source areas in a watershed. Thus, they can be used to target important areas of pollution generation and identify areas best suited for controls on a watershed basis. Moreover, the continuous simulation furnished by some of these models provides an analysis of the relative importance of sources for a range of storm events or conditions. In an effort to reduce complexity and data requirements, these models often are developed for specific applications. For instance, mid-range models can be designed for application to agricultural, urban, or mixed watersheds. Some mid-range models simplify the description of transport processes while emphasizing possible reductions available with controls; others simplify the description of control options and emphasize changes in concentrations as pollutants move through the watershed.

Because mid-range models attempt to use smaller time steps to represent seasonal variability, they require additional meteorologic data (e.g., daily weather data for the GWLF, hourly rainfall for SITEMAP). They also attempt to relate pollutant loadings to hydrologic (e.g., runoff) and erosion (e.g., sediment yield) processes. These models usually include adequate input-output features (e.g., AGNPS, GWLF), making applications easier to process. Several of these models (SITEMAP, Auto-QI) were developed in existing computing environments (e.g., Lotus 1-2-3) to make use of their built-in graphical and statistical capabilities. Neither the simple nor the mid-range models consider degradation and transformation processes, and few incorporate adequate representation of pollutant transport within and from the watershed. Although their applications might be limited to relative comparisons, they can often provide water quality managers with useful information for watershed-level planning decisions.

Selected mid-range models are described below:

■ **Stormwater Intercept and Treatment Evaluation Model for Analysis and Planning (SITEMAP)**

SITEMAP, previously distributed under the name NPSMAP, is a dynamic simulation program that computes, tabulates, and displays daily runoff, pollutant loadings, infiltration, soil moisture, irrigation water demand, evapotranspiration, drainage to ground water, and daily outflows, water, and residual pollutant levels in retention basins or wetland systems (Omicron Associates, 1990). The model can be used to evaluate user-specified alternative control strategies, and it simulates stream segment load capacities in an attempt to develop point source wasteload allocations and nonpoint source load allocations. Probability distributions for runoff and nutrient loadings can be calculated by the model based on either single-event or continuous simulations. The model can be applied in urban, agricultural, or complex watershed simulations. SITEMAP operates within the Lotus 1-2-3 programming environment and is capable of producing graphical output. Although this model requires a minimum calibration effort, it requires moderate effort to prepare input data files. The current version of the program considers only nutrient loading; sediment and other pollutants are not yet incorporated into the program. The model is easily interfaced with GIS (ARC/INFO) to facilitate preparation of land use files. SITEMAP has been applied as a component of a full watershed model to the Tualatin River basin for the Oregon Department of Environmental Quality, and to the Fairview Creek watershed for the Metropolitan Service District in Portland, Oregon.

■ **Generalized Watershed Loading Functions Model**

The GWLF model was developed at Cornell University to assess the point and nonpoint loadings of nitrogen and phosphorus from urban and agricultural watersheds, including septic systems, and to evaluate the effectiveness of certain land use management practices (Haith et al., 1992). One advantage of this model is that it was written with the express purpose of requiring no calibration, making extensive use of default parameters. The GWLF model includes rainfall/runoff and erosion and sediment generation components, as well as total and dissolved nitrogen and phosphorus loadings. The current version of this model does not account for loadings of toxics and metals. The GWLF model uses daily time steps and allows analysis of annual and seasonal time series. The model also uses simple transport routing based on the delivery ratio concept. In addition, simulation results can be used to identify and rank pollution sources and evaluate basinwide management programs and land use changes. The most recent update of the model incorporates a septic (onsite waste water disposal) system component. The model also includes several reporting and graphical representations of simulation output to aid in interpretation of the results. This model was successfully tested on a medium-sized watershed in New York (Haith and Shoemaker, 1987). A version of the model with an enhanced user interface and linkages to national databases, the Watershed Screening Model has recently become available and is distributed with EPA's Office of Wetlands, Oceans and Watersheds Watershed Screening and Targeting Tool.

■ Urban Catchment Model (P8-UCM)

The P8-UCM program was developed for the Narragansett Bay Project to simulate the generation and transport of storm water runoff pollutants in small urban catchments and to assess impacts of development on water quality with minimum site-specific data. It includes several routines for evaluating the expected removal efficiency for particular site plans, selecting or siting BMPs necessary to achieve a specified level of pollutant removal, and comparing the relative changes in pollutant loads as a watershed develops (Palmstrom and Walker, 1990). Default input parameters can be derived from NURP data and are available as a function of land use, land cover, and soil properties. However, without calibration, the use of model results should be limited to relative comparisons. Spreadsheet-like menus and online help documentation make extensive user interface possible. On-screen graphical representations of output are developed for a better interpretation of simulation results. The model also includes components for performing monthly or cumulative frequency distributions for flows and pollutant loadings.

■ Automated Q-ILLUDAS (AUTO-QI)

AUTO-QI is a watershed model developed by the Illinois State Water Survey to perform continuous simulations of storm water runoff from pervious and impervious urban lands (Terstriep et al., 1990). It also allows the examination of storm events or storm sequence impacts on receiving water. Critical events also are identified by the model. However, hourly weather input data are required. Several pollutants, including nutrients, chemical oxygen demand, metals, and bacteria, can be analyzed simultaneously. This model also includes a component to evaluate the relative effectiveness of BMPs. An updated version of AUTO-QI, with an improved user interface and linkage to a GIS (ARC/INFO on PRIME computer), has been completed by the Illinois State Water Survey. This interface is provided to generate the necessary input files related to land use, soils, and control measures. AUTO-QI was verified on the Boneyard Creek in Champaign, Illinois, and applied to the Calumet and Little Rivers to determine annual pollutant loadings.

■ Agricultural Nonpoint Source Pollution Model (AGNPS)

Developed by the U.S. Department of Agriculture (USDA) Agricultural Research Service, AGNPS addresses concerns related to the potential impacts of point and nonpoint source pollution on water quality (Young et al., 1989). It was designed to quantitatively estimate pollution loads from agricultural watersheds and to assess the relative effects of alternative management programs. The model simulates surface water runoff along with nutrient and sediment constituents associated with agricultural nonpoint sources, as well as point sources such as feedlots, waste water treatment plants, and stream bank or gully erosion. The available version of AGNPS is event based; however, a continuous version is under active development (Needham and Young, 1993). The structure of the model consists of a square grid cell system to represent the spatial distribution of watershed properties. This grid system allows the model to be connected to other software such as GIS and digital elevation models. This connectivity can facilitate the development of a number of the model's input parameters. Two new terrain-enhanced versions of the model—AGNPS-C, a contour-based version, and AGNPS-G, a grid-based version—have been developed to automatically generate the grid network and the required topographic parameters (Panuska et al., 1991). Vieux and Needham (1993) describe a GIS-based analysis of the sensitivity of AGNPS predictions to grid-cell size. Engel et al. (1993) present GRASS-based tools to assist with the preparation of model inputs and visualization and analysis of model results. Tim and Jolly (1994) used AGNPS with ARC/INFO to evaluate the effectiveness of several alternative management strategies in reducing sediment pollution in a 417-hectare watershed in southern Iowa. The model also includes enhanced graphical representations of input and output information.

■ Source Loading and Management Model (SLAMM)

The SLAMM model (Pitt, 1993) can identify pollutant sources and evaluate the effects of a number of different storm water control practices on runoff. The model performs continuous mass balances for particulate and dissolved pollutants and runoff volumes. Runoff is calculated by a method developed by Pitt (1987) for small storm hydrology. Runoff is based on rainfall minus initial abstraction and infiltration and is calculated for both pervious and impervious areas. Triangular hydrographs, parameterized by a statistical approach, are used to simulate flow. Exponential buildup and rain washoff and wind removal functions are used for pollutant loadings. Water and sediment from various source areas are tracked by source area as they are routed through various treatment devices. The program considers how particulates filter or settle out in control devices. Particulate removal is calculated based on the design characteristics of the basin or other removal device. Storage and overflow of devices also are considered. At the outfall locations, the characteristics of the source areas are used to determine pollutant loads in solid and dissolved phases. Loads from various source areas are summed. SLAMM has been used in conjunction with a receiving water quality model (Hydrological Simulation Program—FORTRAN, HSPF) to examine the ultimate effects on urban runoff from Toronto for the Ontario Ministry of the Environment. SLAMM also was used to evaluate control options for controlling urban runoff in Madison, Wisconsin, using GIS information (Thum et al., 1990). The State of Wisconsin uses SLAMM as part of its Priority Watershed Program. It was used in Portland, Oregon, for a study evaluating combined sewer overflows.

2. Detailed Watershed Loading Models

Detailed models best represent the current understanding of watershed processes affecting pollution generation. Detailed models are best able to identify causes of problems rather than simply describe overall conditions. If properly applied and calibrated, detailed models can provide relatively accurate predictions of variable flows and water quality at any point in a watershed. The additional precision they provide, however, comes at the expense of considerable time and resource expenditure.

Detailed models use storm event or continuous simulation to predict flow and pollutant concentrations for a range of flow conditions. The models are large and were not designed with emphasis on their potential use by the typical state or local planner. Many of these models were developed to research the fundamental land surface and instream processes that influence runoff and pollutant generation rather than to communicate information to decisionmakers faced with planning watershed management.

Detailed models incorporate the manner in which watershed processes change over time in a continuous fashion rather than rely on simplified terms for rates of change (Addiscott and Wagenet, 1985). They tend to require rate parameters for flow velocities and pollutant accumulation, settling, and decay instead of capacity terms. The length of time steps is variable and depends on the stability of numerical solutions as well as the response time for the system (Nix, 1991). Algorithms in detailed models more closely simulate the physical processes of infiltration, runoff, pollutant accumulation, instream effects, and ground water/surface water interaction. The input and output of detailed models also have greater spatial and temporal resolution. Moreover, the manner in which physical characteristics and processes differ over space is incorporated within the governing equations (Nix, 1991). Linkage to biological modeling is possible because of the comprehensive nature of continuous simulation models. In addition, detailed hydrologic simulations can be used to design potential control actions.

These models use small time steps to allow for continuous and storm event simulations. However, input data file preparation and calibration require professional training and adequate resources. Some of these models (e.g., STORM, SWMM, ANSWERS) were developed not only to support planning-level evaluations but also to provide design criteria for pollution control practices. If appropriately applied, state-of-the-art models such as HSPF and SWMM can provide accurate estimations of pollutant loads and the expected impacts on water quality. New interfaces developed for HSPF and SWMM, and links with GISs, can facilitate the use of complex models for environmental decisionmaking. However, their added accuracy might not always justify the amount of effort and resources they require. Application of such detailed models is more cost-effective when used to address complex situations or objectives.

Selected detailed models are described below.

- **Storage, Treatment, Overflow Runoff Model (STORM)**

STORM is a U.S. Army Corps of Engineers model developed for continuous simulation of runoff quantity and quality, including sediments and several conservative pollutants. It also simulates combined sewer systems (Hydrologic Engineering Center, 1977). STORM has been widely used for planning and evaluation of the tradeoffs between treatment and storage control options for combined sewer overflows. Long-term simulations of runoff quantity and quality can be used for the construction of duration-frequency diagrams. These diagrams are useful in developing urban planning alternatives and designing structural control practices. STORM was primarily designed for modeling storm water runoff from urban areas. It requires relatively moderate to high calibration and input data. STORM was initially developed for mainframe computer usage; however, several versions have been adapted by various individual consultants for use on microcomputers. The model has been applied recently to water quality planning in the city of Austin, Texas (Pantalion et al., 1995).

- **Areal Nonpoint Source Watershed Environment Response Simulation Model (ANSWERS)**

ANSWERS is a comprehensive model developed at the University of Georgia to evaluate the effects of land use, management schemes, and conservation practices or structures on the quantity and quality of water from both agricultural and nonagricultural watersheds (Beasley, 1986). The distributed structure of this model allows for a better analysis of the spatial as well as temporal variability of pollution sources and loads. It was initially developed on a storm event basis to enhance the physical description of erosion and sediment transport processes. Data file preparation for the ANSWERS program is rather complex and requires mainframe capabilities, especially when dealing with large watersheds. The output routines are quite flexible; results may be obtained in several tabular and graphical forms. The program has been used to evaluate management practices for agricultural watersheds and construction sites in Indiana. It has been combined with extensive monitoring programs to evaluate the relative importance of point and nonpoint source contributions to Saginaw Bay. This application involved the computation of unit area loadings under different land use scenarios for evaluation of the tradeoffs between load allocations and wasteload allocations. Recent model revisions include improvements to the nutrient transport and transformation subroutines (Dillaha et al., 1988). Bouraoui et al. (1993) describe the development of a continuous version of the model.

■ Multi-Event Urban Runoff Quality Model (DR3M-QUAL)

DR3M is a watershed model for routing storm runoff through a branched system of pipes and/or natural channels using rainfall as input. The model provides detailed simulation of storm runoff periods selected by the user and a daily soil moisture accounting between storms. Kinematic wave theory is used for routing flows over contributing overland flow areas and through the channel network. Storm hydrographs may be saved for input to DR3M-QUAL, which simulates the quality of surface runoff from urban watersheds. The model simulates impervious areas, pervious areas, and precipitation contributions to runoff quality, as well as the effects of street sweeping and/or detention storage. Variations of runoff quality are simulated for user-specified storm runoff periods. Between these storms, a daily accounting of the accumulation and washoff of water-quality constituents on effective impervious areas is maintained. Input to the model includes the storm hydrographs, usually from DR3M. The program has been reviewed extensively within the USGS and applied to several urban modeling studies (Brabets, 1986; Guay, 1990; Lindner-Lunsford and Ellis, 1987) .

■ Simulation for Water Resources in Rural Basins—Water Quality (SWRRBWQ)

The SWRRBWQ model was adapted from the field-scale CREAMS model by USDA to simulate hydrologic, sedimentation, nutrient, and pesticide movement in large, complex rural watersheds (Arnold et al., 1989). SWRRBWQ uses a daily time step to evaluate the effect of management decisions on water, sediment yields, and pollutant loadings. The processes simulated within this model include surface runoff, percolation, irrigation return flow, evapotranspiration, transmission losses, pond and reservoir storage, sedimentation, and crop growth. The model is useful for estimating the order of magnitude of pollutant loadings from relatively small watersheds or watersheds with fairly uniform properties. Input requirements are relatively high, and experienced personnel are required for successful simulations. SWRRBWQ was used by the National Oceanic and Atmospheric Administration to evaluate pollutant loadings to coastal estuaries and embayments as part of its national Coastal Pollution Discharge Inventory. The model has been run for all major estuaries on the East Coast, West Coast, and Gulf Coast for a wide range of pollutants (Donigian and Huber, 1991). Although SWRRBWQ is no longer under active development, the technology is being incorporated into the Soil and Water Assessment Tool as part of the Hydrologic Unit Model for the United States project at Temple, Texas (Arnold et al., 1993; Srinivasan and Arnold, 1994). EPA's Office of Science and Technology (OST) recently developed a Microsoft Windows-based interface for SWRRBWQ to allow convenient access to temperature, precipitation, and soil data files.

■ Storm Water Management Model (SWMM)

SWMM is a comprehensive watershed-scale model developed by EPA (Huber and Dickinson, 1988). It was initially developed to address urban storm water and assist in storm event analysis and derivation of design criteria for structural control of urban storm water pollution, but it was later upgraded to allow continuous simulation and application to complex watersheds and land uses. SWMM can be used to model several types of pollutants provided that input data are available. Recent versions of the model can be used for either continuous or storm event simulation with user-specified variable time steps. The model is relatively data intensive and requires special effort for validation and calibration. Its application in detailed studies of complex watersheds might require a team effort and highly trained personnel. SWMM has been applied to address various urban water quantity and quality problems in many locations in the United States and other countries (Donigian and Huber, 1991; Huber, 1992). In addition to developing comprehensive watershed-scale planning, typical uses of SWMM include predicting combined sewer overflows, assessing the effectiveness of BMPs, providing input to short-time-increment dynamic receiving water quality models, and interpreting receiving water quality monitoring data (Donigian and Huber, 1991). Warwick and Tadepalli (1991) describe calibration and verification of SWMM on a 10-square-mile urbanized watershed in Dallas, Texas. Tsihrintzis et al. (1995) describe SWMM applications to four watersheds in South Florida representing high- and low-density residential, commercial, and highway land uses. Ovbiebo and She (1995) describe another application of SWMM in a subbasin of the Duwamish River, Washington. OST distributes a Microsoft Windows interface for SWMM that makes the model more accessible. A postprocessor allows tabular and graphical display of model results and has a special section to help with model calibration.

■ Hydrological Simulation Program—FORTRAN (HSPF)

HSPF is a comprehensive package developed by EPA for simulating water quantity and quality for a wide range of organic and inorganic pollutants from agricultural watersheds (Bicknell et al., 1993). The model uses continuous simulations of water balance and pollutant generation, transformation, and transport. Time series of the runoff flow rate, sediment yield, and user-specified pollutant concentrations can be generated at any point in the watershed. The model also includes instream quality components for nutrient fate and transport, biological oxygen demand, dissolved oxygen, pH, phytoplankton, zooplankton, and benthic algae. Statistical features are incorporated into the model to allow for frequency-duration analysis of specific output parameters. Data requirements for HSPF are extensive, and calibration and verification are recommended. The program is maintained on IBM microcomputers and DEC/VAX systems. Because of its comprehensive nature, the HSPF model requires highly trained personnel. It is recommended that its application to real case studies be carried out as a team effort. The model has been extensively used for both screening-level and detailed analyses. HSPF is being used by the Chesapeake Bay Program to model total watershed contributions of flow, sediment, nutrients, and associated constituents to the tidal region of the Bay (Donigian et al., 1990; Donigian and Patwardhan, 1992). Moore et al. (1992) describe an application to model BMP effects on a Tennessee watershed. Scheckenberger and Kennedy (1994) discuss how HSPF can be used in subwatershed planning. Ball et al. (1993) describe an application of HSPF in Australia. Lumb et al. (1990) describe an interactive program for data management and analysis that can be effectively used with HSPF. Lumb and Kittle (1993) present an expert system that can be used for calibration and application of HSPF.

Using the Walker BATHTUB Model in Lake Pepin, Minnesota

BATHTUB was developed for modeling reservoir water quality and is based on empirical data from U.S. Army Corps of Engineers' reservoirs (Walker, 1986). BATHTUB is routinely used in Clean Water Partnership (CWP) nonpoint source studies and for determining the need for effluent-P limitations in Minnesota. The CWP studies are similar to Clean Lakes Phase I studies and are typically designed to obtain accurate estimates of water and P loading from a lake's major subwatersheds. FLUX, a data reduction tool, is used to reduce flow and concentration data and provide accurate estimates of average flow and concentration (typically flow-weighted means) for the period of concern (typically one water year). Flow-weighted mean concentrations and flow data are used in BATHTUB. BATHTUB allows for segmentation of a lake or reservoir and can be used to route flows and loads between a series of lakes, thus accounting for upstream sedimentation. BATHTUB, Version 5.3 (Walker, 1996) also allows estimation of internal phosphorus loading.

In the absence of monitored data (e.g., small subwatersheds) phosphorus loading may be estimated based on land use composition of the subwatershed, runoff coefficients, and literature-based phosphorus concentrations for a specific land use (e.g. Walker, 1985b). This is often the case when determining effluent-phosphorus limits where detailed loading data are seldom available. In many instances with small dischargers (typically less than 1 MGD) some in-lake data are available, plant discharge is known, and background watershed phosphorus loading is estimated. BATHTUB is then used to determine the "effect" of the discharge on the lake and the need for an effluent-P limitation (typically 1 mg P/L) on the discharge to protect the condition of the lake.

BATHTUB was used to help establish a chlorophyll *a* goal for Lake Pepin, a run-of-the-river reservoir on the Mississippi River between Minnesota and Wisconsin (Heiskary and Walker, 1995). A major interagency study of Lake Pepin and the Mississippi River was initiated in 1990 in response to major nuisance algal blooms, which occurred during the low-flow summer of 1988, and to assess the impact of the 250 MGD Metropolitan Council's Metro wastewater treatment facility located 80 kilometers upstream of the lake. In Lake Pepin inorganic turbidity and flow, in addition to phosphorus, strongly influence chlorophyll *a* concentrations. By choosing a model subroutine which accounted for these factors, reliable estimates of chlorophyll *a*, as a function of flow (residence time) and inflow phosphorus concentration were made. In turn, the in-lake phosphorus concentration required to achieve the chlorophyll *a* goal of 30 µg/L (and thus minimize the frequency of severe nuisance blooms) over a range in flow conditions was estimated. The flows of concern in this case ranged from about 4,600 cfs (2% reoccurrence) up to about 20,000 cfs (50% reoccurrence). A flow of 20,000 cfs corresponded to a residence time of about 11 days in Lake Pepin. Concurrent modeling of Lake Pepin by the Metropolitan Council using WASP provided comparable results (Lung and Larson, 1995).

Both modeling efforts raised questions about the role of internal loading in this system and to what degree internal loading might inhibit recovery of the system (even with substantial reductions in external loading). Subsequent permit negotiations led to (1) interim phosphorus limits at the Metro Plant; (2) provisions to pursue bio-phosphorus removal in a portion of the plant; and (3) further modeling of Lake Pepin and the Mississippi River to better understand the relationship between external loading, internal recycling, and the production of algae in the reservoir. More recent permit negotiations (1998-99) led to permanent phosphorus limits for the Metro Plant that will be accomplished through biological phosphorus removal. Detailed mechanistic modeling, conducted as a requirement of the previous permit, provided an improved understanding of this complex run-of-the-river reservoir. However, questions remained on the magnitude of internal loading and how this might influence the overall recovery of this system with reductions in external P loading.

CASE STUDY: The Minnesota Approach to Lake Eutrophication Modeling

The Minnesota Pollution Control Agency (MPCA) uses a suite of models in the course of lake eutrophication studies. Applications include: goal setting during Lake Assessment Program (LAP) studies; defining water and nutrient mass-balances during nonpoint source (Clean Water Partnership) studies; and establishing effluent-phosphorus limits for municipal and industrial wastewater discharges to lakes. The choice of model is dictated by the availability of data and the degree of precision required in the modeling estimate. For example, the establishment of effluent phosphorus limits for large dischargers requires greater precision than is required for a simple goal-setting exercise. The suite of models used by MPCA include (1) a simple regression model for predicting background phosphorus concentrations, (2) an ecoregion-based model, (3) spreadsheet methodologies based on the Reckhow and Simpson (1980) technique, (4) the BATHTUB model, and (5) mechanistic applications such as WASP. All of these models have been used as a basis for goal setting and can also be used to develop nutrient criteria, to predict whether lakes may achieve certain criteria levels, or to determine how point or nonpoint sources of phosphorus may impact a lake.

A regression model developed by Vighi and Chiaudani (1985), which is based on the morphoedaphic index (commonly used in fishery science), is frequently used in Minnesota to estimate background TP for lakes during LAP studies. The regression equation predicts TP based on lake morphometry (mean depth) and alkalinity or conductivity and provides a quick estimate of background phosphorus concentrations for a lake. When used in conjunction with reference-lake data sets and other models it can be very useful for goal setting. It may also be particularly useful for developing phosphorus criteria in regions where background conditions are assumed to be naturally oligotrophic to mesotrophic because the model-development data set is based on oligotrophic and mesotrophic lakes. This model is best used in conjunction with other tools and data sets and may be of limited value for goal setting in very shallow lakes, lakes with excessive internal loading, or lake/reservoir chains.

The "Minnesota Lake Eutrophication Analysis Procedures" (MINLEAP), was developed by MPCA staff based on an analysis of data collected from the reference lakes in each of Minnesota's ecoregions. It is intended to be used as a screening tool for estimating lake conditions with minimal input data (lake mean depth and surface area, watershed area, ecoregion, and some observed data for comparison). MINLEAP is described in greater detail in Wilson and Walker (1989). Routine data from minimally-impacted streams in each ecoregion are used as one basis for estimating inflow TP concentrations. Annual precipitation, evaporation, and runoff are summarized based on Minnesota Department of Natural Resources and USGS data and regionalized for use in the model (Wilson, 1990). The model predicts in-lake phosphorus concentrations based on the Canfield and Bachmann (1981) natural lake equation. Chlorophyll *a* and Secchi are estimated based on regression equations developed from the ecoregion-reference lake data set. In addition, nuisance frequencies of chlorophyll *a* are predicted based on equations developed by Walker (1985a). These nuisance frequency predictions are particularly useful for communicating the impact of increasing in-lake phosphorus concentrations to lake users and local governments.

The MINLEAP procedure has been extremely useful for quickly screening lake condition and as a basis for goal setting. The Vighi and Chiaudani regression is built into the model and allows for comparisons between the two methodologies. The MINLEAP model tends to work best for headwater lakes or lakes with moderate-sized watersheds. The model will tend to over-predict in-lake phosphorus concentrations for lakes with large watersheds or for chains of lakes, since upstream sedimentation is not specifically incorporated into the model. The program was originally written in BASIC but has been converted for use in Windows, thus increasing its utility and making it potentially adaptable for additional ecoregions or for use in other states.

The next level of modeling routinely employed by Minnesota is the Reckhow and Simpson spreadsheet model. This spreadsheet is based on Reckhow and Simpson (1980) and underlying concepts are discussed in greater detail in Wilson (1990). This model relies on phosphorus export coefficients and land uses as a basis for estimating phosphorus loading to a lake. Runoff coefficients and regional precipitation and evaporation data are used to estimate the lake water budget. This type of model can be useful for estimating the impact of changes in land use and making general estimates of the relative contributions to the in-lake phosphorus concentration from a variety of sources such as the watershed (e.g., soils), precipitation, and shoreland septic systems. The accuracy of the estimates is dependent on good land use data, appropriate phosphorus export coefficients for the region, and reliable in-lake data to initially test the model.

Appropriate phosphorus export coefficients are often a shortcoming of the Reckhow and Simpson technique. This is especially true for lakes with large watersheds and/or lakes which have extensive lake or wetland areas in their watershed. In these instances, routinely published export coefficients will often overestimate actual phosphorus loading and produce unreliable estimates. Prairie and Kalff (1986) provide some regression equations that account for the size of the watershed, predominant land use, and the retention of phosphorus that occurs in large watersheds. This often yields more reasonable export estimates.

The MPCA version of the Reckhow-Simpson spreadsheet was modified by Wilson to include a methodology which allows for an estimate of the potential loading from feedlots in the watershed (Heiskary and Wilson, 1996). This analysis is based on estimates of animal units and literature estimates of phosphorus generated per animal. This feature is useful in watersheds with extensive feedlots or pasturing operations since routinely cited phosphorus exports for "pastured use" do not typically account for the high phosphorus exports arising from feedlots (Shuler, 1995). Although a spreadsheet model of this type may have many shortcomings, it often is the only readily available model that can be used to estimate land use changes in the watershed when data are very limited (as is often the case for local governments needing to assess the impact of small scale land use changes on the quality of a lake).

Several other methodologies are somewhat similar to that described here but more widely available and may be useful for developing or testing nutrient criteria or assessing the impact of land use changes in a lake's watershed. Prominent among these would be EUTROMOD (Reckhow, 1990) and the Wisconsin Lake Model Spreadsheet (WILMS; Panuska et al., 1994). These two models and related models for assessing the impact of development in a watershed (such as Pondnet and Pondsiz) are readily available from the North American Lake Management Society (Phone: 608-233-2836).